

FERMILAB-Pub-97/381-A  
 astro-ph/9711110  
 submitted to *Astrophys. J. (Lett.)*

## No Need for MACHOS in the Halo

Evalyn I. Gates,<sup>1,2</sup> Geza Gyuk,<sup>3</sup> Gilbert P. Holder,<sup>2</sup> and Michael S. Turner<sup>2,4,5</sup>

<sup>1</sup>*Adler Planetarium & Astronomy Museum, Chicago, IL 60605*

<sup>2</sup>*Department of Astronomy & Astrophysics, The University of Chicago, Chicago, IL 60637-1433*

<sup>3</sup>*S.I.S.S.A., via Beirut 2-4, 34014 Trieste, Italy*

<sup>4</sup>*Department of Physics, Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637-1433*

<sup>5</sup>*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500*

### ABSTRACT

A simple interpretation of the more than dozen microlensing events seen in the direction of the LMC is a halo population of MACHOs which accounts for about half of the mass of the Galaxy. Such an interpretation is not without its problems, and we show that current microlensing data can, with some advantage, be explained by dark components of the disk and spheroid, whose total mass is only about 10% of the mass of the Galaxy.

*Subject headings:* dark matter — MACHOs

## 1. Introduction

Microensing surveys probe the baryonic matter in our Galaxy that exists in dark compact objects (MACHOs). These surveys have to date focused on fields toward the LMC and toward the galactic bulge, although current and future surveys are probing other lines of sight including the SMC (Palanque-DeLabrouille et al. 1997, Alcock et al. 1997a). The LMC events include microlensing of LMC stars by disk, halo, and spheroid lenses, as well as LMC-LMC self lensing. Contributions to the microlensing optical depth from known populations in each of these components has been calculated, and their sum is significantly less (by about a factor of four) than the current estimate,  $\tau_{\text{LMC}} = (2.1^{+1.1}_{-0.7}) \times 10^{-7}$  (Alcock et al. 1997b). Microlensing has apparently revealed a previously undetected dark population of objects.

On the face of it, the simplest explanation is that the dark halo has a significant (order 20% to 80%) MACHO component. However, under this assumption, the inferred lens mass is around  $0.5M_{\odot}$ , which is difficult to reconcile with searches for white dwarfs and subdwarfs in the Hubble Deep Field and other surveys (Graff & Freese 1996, Flynn, Gould & Bahcall 1996), and, at the very least, requires a population of objects with an unusual initial mass function. Other studies indicate that there must be 3 to 10 times more mass in processed and unprocessed gas than in MACHOs (Fields, Matthews & Schramm 1997). There is no evidence for such a large amount of gas, and the huge mass implied may not be consistent with the mass budget for the Local Group.

In addition, there is evidence that most of the baryonic dark matter in the Universe exists in the form of diffuse hot gas, rather than MACHOs. In rich clusters the mass in hot, x-ray emitting gas is about ten times that in luminous matter in cluster galaxies; this is consistent with the ratio of the fraction of critical density in baryons (as determined by big-bang nucleosynthesis) to that in luminous matter. Further, if the cluster gas fraction is taken as a fair sample for matter in the Universe, gas present when clusters formed accounts for the bulk of the baryons in the Universe (e.g., Evrard 1997). Further, detailed comparison of the opacity of the Lyman- $\alpha$  forest with numerical simulations indicate that the total amount of baryons in gas at redshifts  $z \sim 2-4$  accounts for all the baryons. Finally, hydrodynamical simulations of structure formation indicate that most of the baryons remain in

diffuse hot gas (Cen et al. 1994).

While microlensing surveys of the LMC probe the halo only out to a distance of 50 kpc, the Galactic halo extends to at least twice this distance. If MACHOs represent a significant fraction of the halo, they alone eat up most of the baryon-mass budget, leaving little room for baryonic gas. In the context of the cold dark matter paradigm, which provides the only currently viable models for the evolution of structure in the Universe, it is difficult – though not impossible – to understand half the mass of the Galaxy being in MACHOs (Gates & Turner 1994, Dodelson, Gates & Turner 1996).

There are alternatives to halo MACHOs. Sahu (1994) has argued that the lenses could be in the LMC itself, though it seems difficult to achieve the measured optical depth (Gould 1995). Zhao has suggested that the MACHOs reside in a previously undetected dwarf galaxy located in front of the LMC (Zhao 1996) or in tidal debris in the Magellanic Stream (Zhao 1997). Evidence has been presented for (Zaritsky & Lin 1997) and against this hypothesis (Alcock et al. 1997c). Finally, the possibility that the lenses are more distant disk stars that lie along the line-of-sight to the LMC because of warping and flaring of the Galactic disk has also been suggested (Evans, Gyuk, Turner & Binney 1997).

Two, more modest, alternatives involve dark extensions of known galactic populations, the thick disk (Gould 1994, Gould, Miralda-Escude & Bahcall 1994) and the spheroidal (Giudice, Mollerach & Roulet 1994). Such models are appealing for several reasons. The disk and the spheroid contain significant visible populations, and MACHOs would be the dark, unseen population. In fact, dynamical studies indicate a significant dark population in each. Finally, such MACHOs will contribute far less to the total baryon mass in the Galaxy than MACHOs in an isothermal halo.

In this *Letter* we explore the viability of the hypothesis that all the microlensing events can be explained with dark extensions of the disk and spheroid stellar populations. We show that models of the Galaxy which are consistent with the bulge and LMC microlensing data and which have no MACHOs in the dark halo can be constructed.

## 2. Methods

The methods employed are similar to those of Gates, Gyuk & Turner 1996. Galactic models were constructed by varying the Galactic parameters relevant to the problem independently over a range of values consistent with observational data. These models were then constrained by data on the Galactic rotation curve and by the microlensing results for the bulge. Surviving models were binned by  $\tau_{\text{LMC}}$ .

Our models consist of five components: central bulge, thin disk, thick disk, spheroid and dark halo. The baryonic dark matter in MACHOs resides in the thick disk and spheroid; the thin disk represents the non-lensing component (e.g., gas and bright stars) of the visible disk; and the halo is comprised solely of nonlensing dark matter, such as cold dark matter.

The thin disk, which does not contribute to microlensing, was taken to have an exponential profile in both  $z$  and  $R$ , with scale lengths  $h_z = 0.3 \text{ kpc}$  and  $R_d = 3.5 \text{ kpc}$  and total surface mass density  $25 M_\odot \text{ pc}^{-2}$ . We varied the surface mass density of the thick-disk component, with the requirement that the total projected mass density within  $1.1 \text{ kpc}$  of the Galactic plane be in the range  $(35 - 85) M_\odot \text{ pc}^{-2}$ . The scale height of the thick disk was allowed to vary between  $1 \text{ kpc}$  and  $2.5 \text{ kpc}$ .

We considered two families of thick disks: exponential disks with radial scale length  $R_d$  in the range  $(3 - 4) \text{ kpc}$ , and Mestel disks, with a surface density  $\propto R^{-1}$ . While a thick disk population is often assumed to have the same radial density profile as the observed thin disk, there is no a priori reason to expect this, especially given the different formation histories expected of the two populations.

Estimates of the power-law index of the spheroid distribution depend on the tracer population studied, with an index of  $-3$  obtained from star counts (Saha 1985), and from  $-3$  to  $-3.5$  from globular cluster counts (Frenk & White 1982). Different amounts of dissipation may have occurred in the two populations before formation. We assume a density profile  $\rho(r) \propto b^3/(b^3 + r^3)$  for the spheroid component, with core radius  $b < 2 \text{ kpc}$ .

Evidence is mounting that the central region of our Galaxy is dominated by a bar-like object. It does not contribute to microlensing to the LMC, but it is important for both microlensing toward the Galactic center and for its effect on the inner rotation curve. We used the G2 model of Dwek et al. 1995

for the bar, and its total mass was constrained to  $(1 - 4) \times 10^{10} M_\odot$ , with long axis chosen to lie at an angle of  $13.4^\circ$  with respect to the line-of-sight to the Galactic center. The exact details of the bulge model are only important for calculating the microlensing optical depth toward the bulge and do not affect our conclusions significantly.

The massive dark halo of the Galaxy was represented by a cored isothermal sphere of nonlensing objects, with core radius  $(2 - 12) \text{ kpc}$ .

The two most important Galactic structure parameters are the rotation speed at the solar circle,  $v_o$ , and the solar distance from the Galactic center,  $R_0$ . We incorporated the uncertainties in these parameters by allowing them to vary independently:  $200 \text{ km/s} \leq v_o \leq 240 \text{ km/s}$  and  $7.0 \text{ kpc} \leq R_0 \leq 9.0 \text{ kpc}$ .

All models were then subjected to constraints coming from the observed rotation curve and from microlensing results toward the Galactic bulge. The rotation curve was required to be approximately flat (not be rising or falling by more than 14%) between  $4$  and  $18 \text{ kpc}$  from the Galactic center, and to be in the range  $150\text{--}307 \text{ km/s}$  at  $50 \text{ kpc}$ .

The optical depth toward the Galactic bulge probes (and constrains) the mass distribution in the inner Galaxy, which in turn constrains the other components (Gates, Gyuk & Turner 1996). We required viable models to have an optical depth toward Baade's window ( $b = -4^\circ, l = 1^\circ$ ) greater than  $2.0 \times 10^{-6}$ , which is conservative lower bound to  $\tau_{\text{bulge}}$  based on data from the OGLE (Udalski et al. 1994) and MACHO (Alcock et al. 1997d) collaborations.

## 3. Results

Figures 1-3 characterize the viable models. The range of each parameter is shown as a function of  $\tau_{\text{LMC}}$ . Viable Galactic models were found for  $\tau_{\text{LMC}}$  as large as  $2.5 \times 10^{-7}$ . Not surprisingly, higher values of  $\tau_{\text{LMC}}$  have smaller ranges for all of the parameters, indicating that these models occupy a small portion of the parameter space.

Fig. 1 illustrates that large  $\tau_{\text{LMC}}$  requires a combination of large local rotation speed and small Galactocentric distance: In order to achieve high optical depths, a model needs as much lensing material as possible in the inner galaxy. Measurements of  $v_o$  and  $R_0$  are not independent, however. The combination of Oort's constants  $A - B = v_o/R_0$  is constrained. An analysis by Kerr & Lynden Bell (1986) found

$A - B = 26.4 \pm 1.9$  km/s/kpc. A more recent analysis of Hipparcos proper motions by Feast & Whitelock (1997) finds  $A - B = 27.19 \pm 0.87$  km/s/kpc. With the upper limit  $A - B \leq 30$  km/s/kpc, no model with an exponential disk can produce  $\tau_{\text{LMC}} \gtrsim 1.6 \times 10^{-7}$ , and no model with a Mestel disk can produce  $\tau_{\text{LMC}} \gtrsim 2.2 \times 10^{-7}$ .

Overall, the Mestel disk can produce a significantly higher optical depth toward the LMC. For a given surface density, the contribution of a Mestel disk to the inner rotation curve is smaller than that of an exponential disk. Thus, models with a Mestel disk can have a higher disk surface density without exceeding limits on the observed rotation curve. Further, the spheroid can be heavier in models with a Mestel disk, again providing more LMC lenses.

The spheroid mass, total MACHO mass,<sup>1</sup> and relative contributions of the disk and spheroid as a function of optical depth to the LMC are shown in Figs. 2 and 3. While  $M_{\text{spheroid}}$  and  $\Sigma$  both show a fair amount of scatter, the combined mass of the lensing populations is more tightly constrained. The MACHO collaboration notices a similar effect for their halo models (Alcock et al. 1996).

The required spheroid mass increases with  $\tau_{\text{LMC}}$ , in some cases becoming comparable to the visible mass of the disk. Estimates of the dynamical mass in the spheroid are roughly in the range of  $(5 - 7) \times 10^{10} M_{\odot}$  (Caldwell & Ostriker 1981), while the luminous mass is considerably less, around  $(1 - 3) \times 10^{10} M_{\odot}$  (Bahcall, Schmidt & Soneira 1983). The spheroid mass in Mestel disk models is consistent with these estimates; in exponential disk models these estimates restrict  $\tau_{\text{LMC}} \lesssim 2 \times 10^{-7}$ , as they require a heavier spheroid.

The growing importance of the spheroid for large values of  $\tau_{\text{LMC}}$  is also seen in the last panel in Figs. 2 and 3. Basically there is an upper bound to the amount of lensing that can be done by the disk, especially an exponential disk, so that a large optical depth can only come with a substantial spheroid contribution.

It has been suggested that alternate lines of sight can help break the degeneracy between Galactic models. However, the high-latitude bulge fields and the

SMC do not offer much hope in this respect. For example, the signature of flattening suggested by Sackett & Gould (1993), where the SMC optical depth is enhanced relative to the LMC for a flattened halo, can also be reproduced by models with a thick disk, while a very heavy spheroid can produce the signal expected of a spherical halo. The high-latitude bulge fields suffer from the problem that there is a fixed amount of optical depth toward the bulge itself which must be accounted for. We find that any model that can produce this bulge optical depth also produces roughly the same optical depth toward high-latitude bulge fields. This is true for scenarios both with and without MACHOs in the Galactic halo. Globular clusters hold more promise (Gyuk & Holder 1997), but their feasibility as a target for microlensing surveys is still under investigation.

#### 4. Discussion

We have found viable Galactic models in which MACHOs in dark extensions of the thick disk and spheroid alone produce an optical depth for microlensing toward the LMC of around  $2 \times 10^{-7}$ . Thus, at present, microlensing does not require a significant halo MACHO population.

The mass in MACHOs in our Galactic models is only a small fraction of the total Galactic mass, of order 10%. This is in line with the evidence that most of the dark baryons are in gaseous form, and the cold dark matter paradigm, which holds that most of the mass of the Galaxy should be cold dark matter particles. On the other hand, in Galactic models where the MACHOs are a significant fraction of an isothermal halo which extends to 100 kpc or more, MACHOs comprise around almost half of the total mass in the Galaxy; this is difficult to reconcile with most of the dark matter being nonbaryonic and most of the baryons being gaseous.

The estimate for the average mass of the lenses in our models is only slightly lower than that determined for halo MACHO models,  $\langle m \rangle \sim 0.3 M_{\odot}$  ( $0.2 M_{\odot}$  for disk lenses and  $0.36 M_{\odot}$  for spheroid lenses), compared with  $0.5 M_{\odot}$  for halo lenses. The puzzle of what the lenses are remains. However, it should be noted that the baryon mass budget problem is far less severe, and the constraints from direct searches for lenses may be less severe because the lenses are not distributed like the halo (Gyuk & Gates 1997).

Better measurements of  $v_0$ ,  $R_0$ ,  $\tau_{\text{LMC}}$ , and the

<sup>1</sup>For the Mestel disk, this involves a cut-off to the density distribution in order to keep the mass finite. We chose to truncate the disk at 15 kpc. The total disk mass scales linearly with this truncation radius.

Galactic rotation curve hold leverage in testing the spheroid/heavy disk hypothesis. Parallax measurements of the lensing events, which allow an estimate of the distance to the lens, and/or future lensing surveys towards globular clusters, which probe additional lines of sight through the Galaxy can also distinguish between halo and nonhalo models.

This work was supported in part by the DOE (at Chicago and Fermilab) and by the NASA (through grant NAG5-2788).

## REFERENCES

- Alcock, C. et al. 1997a, astro-ph/9708190
- Alcock, C., et al. , 1997b, ApJ, 486, 697
- Alcock, C., et al. , 1997c, astro-ph/9707310
- Alcock, C., et al. 1997d, ApJ, 479, 119
- Bahcall, J.N., Schmidt, M., & Soneira, R.M. 1983, ApJ, 265, 730
- Caldwell, J.A.R. & Ostriker, J.P. 1981, ApJ, 251, 61
- Cen, R., Miralda-Escude, J., Ostriker, J.P. & Rauch, M. 1994, ApJ, 437, L9
- Dodelson, S., Gates, E. & Turner, M.S. 1996, Science, 274, 69
- Dwek, E. et al. 1995, ApJ, 445, 716
- Evans, N.W., Gyuk, G., Turner, M.S. & Binney, J., Nature, submitted
- Evrard, A.E., astro-ph/9710148
- Feast, M. & Whitelock, P. 1997, astro-ph/9706293
- Fields, B.D., Matthews, G. & Schramm, D. 1997, ApJ, 483, 625
- Flynn, C., Gould, A. & Bahcall, J. 1996, ApJ, 466, L55
- Frenk, C. & White, S.D.M. 1982, MNRAS, 198, 173
- Gates, E. & Turner, M.S. 1994, Phys. Rev. Lett., 72, 2520
- Gates, E., Gyuk, G., & Turner, M.S. 1996, Phys. Rev. D, 53, 4138
- Giudice, G.F., Mollerach, S. & Roulet, E. 1994, Phys. Rev. D, 50, 2406
- Gould, A. 1994, ApJ, 421, L71
- Gould, A. 1995, ApJ, 441, 77
- Gould, A., Miralda-Escude, J. & Bahcall, J.N. 1994, ApJ, 423, L105
- Graaf, D. & Freese, K. 1996, ApJ, 456, L49
- Gyuk, G. & Gates, E. 1997, in preparation
- Gyuk, G. & Holder, G. 1997, astro-ph/9710251
- Kerr, F.J. & Lynden-Bell, D. 1986, MNRAS, 221, 1023
- Palanque-Delabrouille, N. et al. 1997, astro-ph/9710194
- Sackett, P. & Gould, A. 1993, ApJ, 419, 648
- Saha, A. 1985, ApJ, 289, 310
- Sahu, K. 1994, Nature, 370, 275
- Udalski, A. et al. 1994, Acta Astronomica, 44, 165
- Zaritsky, D. & Lin, D.N.C. 1997, astro-ph/9709055
- Zhao, H.-S. 1996, astro-ph/9606166
- Zhao, H.-S. 1997, astro-ph/9703097

## Figure Captions

1. Range of  $v_o$ ,  $R_0$  and the Oort constants ( $A - B$ ) as a function of  $\tau_{\text{LMC}}$  for viable models with MACHOs in a thick exponential disk (solid line) and in a thick Mestel disk (dashed line); scale height is 1.5 kpc.
2. Range of parameters for viable models with MACHOs in a thick exponential disk with scale heights 1.0 kpc (solid square), 1.5 kpc (open square), 2.0 kpc (solid triangle), and 2.5 kpc (open triangle). From top to bottom: Spheroid mass; total mass in baryons; and ratio of the spheroid to disk contributions to  $\tau_{\text{LMC}}$ .
3. Same as Fig. 2 for thick Mestel disk models.





